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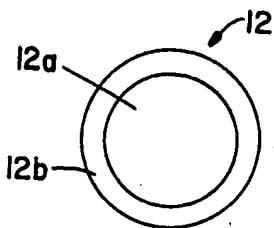
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(54) Title: COATED PARTICLES AND METHODS OF COATING PARTICLES



(57) Abstract

Methods of coating nanoparticles (30) with one or more layers of various types of materials such as metals (30b), polymers (30c) and halides (30d), and nanoparticles formed by those methods. A first embodiment of the invention is a method of forming silver halide (12b) coated dielectric nanoparticles (12a), and a second embodiment is a method of forming metal (14b) coated dielectric nanoparticles (14a). A first nanoparticle according to this invention comprises a dielectric nano-core and a silver halide coating; and a second nanoparticle comprises a dielectric nano-core, a metal shell over that core and a silver halide (14c) coating over the metal shell. A further nanoparticle of this invention comprises a dielectric nano-core (16a), a silver halide shell (16b) over the core and a metal shell (16c) over the silver halide; and a still further nanoparticle comprises a dielectric core (20a), a first shell of a first metal (20b) and a second shell (20c) of a second metal.

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-1-

## 1 COATED PARTICLES AND METHODS OF COATING PARTICLES

Background of the Invention

5 This invention generally relates to methods of coating particles; and, more specifically, to methods that are well suited for coating nanoparticles and to the particles formed by those methods.

10 Nanoparticles are particles having a size on the order of magnitude of  $10^{-7}$  m. While such particles are known, per se, heretofore, these particles have not been extensively used. For several reasons, though, it is believed that nanoparticles will have very important commercial 15 applications in the future. For example, in some cases, such as in photographic emulsions, nanoparticles coated with a given material may be suitable replacements for, and cost less than, larger, solid particles made from that given material. In addition, nanoparticles can be constructed so as to exhibit an enhanced plasmon resonance effect, which is the enhancement of electromagnetic fields in and around those 20 particles, and these particles may be used in numerous specific methods and devices to enhance photo or optical processes that occur in those methods and devices. In other applications, nanoparticles may be very useful as nucleation centers, which may be used to form larger particles having 25 specific constructions.

SUMMARY OF THE INVENTION

30 An object of this invention is to provide new, coated particles, and new methods for coating particles. Another object of this invention is to coat

-2-

1 nanoparticles with one or more layers of various types of materials such as metals, polymers and halides.

5 A further object of the present invention is to provide a nanoparticle, and a method that may be used to form a nanoparticle, having a dielectric core coated with metal halide, such as silver halide.

10 A further object of this invention is to provide a method that may be used to coat dielectric nanoparticles with a layer of a metal.

15 Another object of the present invention is to provide a nanoparticle, and a method that may be used to form a nanoparticle, having a dielectric core covered with one shell of metal and another shell of a metal halide, e.g., silver halide.

20 These and other objects are attained with various methods for coating particles and the particles formed by those methods. A first embodiment of this invention is a method for forming metal halide, e.g., silver halide, coated dielectric particles, comprising the steps of providing a source of metal ions and a source of halide ions in a liquid carrier having dispersed therein charged colloidal dielectric particles, and reacting the halide ions with the metal ions in the presence of the dielectric particles to form coatings of metal halide over individual dielectric particles. A 25 second embodiment of this invention is a method of forming metal coated dielectric nanoparticles, comprising the steps of providing a source of metal ions, a source of an alcohol and a source of a ketone in an anaerobic liquid carrier having dispersed therein charged dielectric particles, and 30 exposing the liquid carrier to light to cause the metal ions

-3-

1 to be reduced and form metal coatings over individual dielectric particles.

In accordance with a third embodiment of this invention, metal coated dielectric nanoparticles are formed by a method comprising the steps of forming metal halide coated nanoparticles, and exposing the coated nanoparticles to light and a reducing agent to change the metal halide to metal to form metal coatings over individual nanoparticles.

5 In a fourth method according to the present invention, metal coated dielectric nanoparticles may also be formed by a method comprising the steps of providing a source of metal ions, a source of halide ions and an election hole scavenger in a liquid carrier having dispersed therein negatively charged colloidal dielectric particles, reacting the metal ions with the halide ions in the presence of the dielectric 10 particles and the election hole scavenger to form metal halide coatings over individual nanoparticles, and exposing the liquid carrier to light and reducing agent to change the 15 metal halide coatings to metal coatings.

20 A fifth embodiment of this invention is a method of forming metal coated dielectric nanoparticles, comprising the steps of providing a liquid carrier having dispersed therein dielectric nanoparticles having metal halide on the surfaces thereof, changing at least a portion of the metal halide on individual nanoparticles to metal, adding metal ions and a sulfate reducing agent to the liquid carrier, and forming metal coatings on the nanoparticles from those metal ions, 25 wherein the metal on the nanoparticles acts as a catalyst and accelerates the formation of the metal coatings.

30 With all of the above-described methods, it is not necessary that any formed coating of a particle completely

-4-

1 cover the core or an underlying coating of the particle. Complete coverage of the core or of another coating may be preferred for certain applications, though, and can also be obtained using the methods of this invention.

5 A first nanoparticle according to this invention comprises a dielectric core, and a metal halide coating over this dielectric core. A second nanoparticle according to the present invention comprises a dielectric core, a metal coating disposed immediately over that core, and a layer of metal halide disposed immediately over that metal layer. A third nanoparticle according to the present invention comprises a dielectric core, a layer of metal halide disposed immediately over that core, and another layer of metal disposed immediately over the metal halide coating. A still 10 15 another nanoparticle according to the present invention comprises a dielectric core, a layer of one metal disposed over that core, and a layer of another metal disposed over that first metal layer.

Any of the nanoparticles formed in accordance with the present invention may be provided with an outer coating of a polymer material to prevent the particle from reacting chemically with any medium or environment in which the particle is used. Also, it may be desirable to provide these nanoparticles formed according to the present invention with interior coats of a polymer material to prevent other coats of the particle from chemically reacting with each other, or to prevent the core of the particle from chemically reacting with a coating of the particle. In addition, in any nanoparticle according to this invention, it is not necessary that any given coating of the particle completely cover the core or another coating of the particle. Such complete

-5-

1 coverage of the core or of another coating may be preferred, however, for certain nanoparticles or for certain uses.

5 Further benefits and advantages of the invention will become apparent from a consideration of the following detailed description given with reference to the accompanying drawings, which specify and show preferred embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

10 Figures 1 through 9, which are not drawn to scale, show various coated nanoparticles of the present invention.

Figures 10 through 18 outline several processes of this invention that may be used to form the particles shown in Figures 1 through 9.

15 Figure 19 is a transmission electron micrograph of silver-coated silver bromide nanoparticles.

Figure 20 is a transmission electron micrograph of silver coated silver bromide nanoparticle treated with ammonia.

20 Figure 21 shows various optical extinction spectra of silver coated silver bromide nanoparticles either untreated or treated with ammonia. The spectra of (a) to (d) are spectra of various illuminated solutions of Ag, Br, and EDTA. In going from (a) to (d), the illumination time increases. The spectrum in(e) is a typical spectrum observed after the addition of ammonia to any of the above solutions.

30 Figure 22 shows computed extinction efficiencies for silver-coated silver bromide particles in water. The diameter of the core particle is 20 nm and the thickness of the silver coats are indicated in nm. The spectrum marked solid is that of a homogeneous 20 nm diameter silver sphere.

-6-

1       Figure 23 is an optical extinction spectrum of a  
measured silver coated silver bromide nanoparticle and two  
computed extinction spectra. The measured spectrum lies  
between the two computed spectra. In the upper curve all the  
5       silver in the coat is assumed to come from the solution. In  
the lower curve all of the silver is assumed to come from the  
reduction of AgBr at the particle surface.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

10       Figures 1 through 9 show various particles all  
formed in accordance with the present invention; and  
generally, each of these particles comprises a dielectric  
core and one or more coatings over that core. The cores of  
all of these particles have sizes on the order of magnitude  
15       of a 0.5 to 200 nanometers, and thus are referred to as  
nano-cores or nanoparticles. With some of these particles,  
such as those shown in Figures 1 through 3, and 7 and 8, one  
coating of each particle is comprised of silver halide; and  
with some of these particles such as those shown in Figures 2  
20       through 6, 8 and 9 at least one coating of each particle is  
comprised of a metal.

25       Particle 12 of Figure 1 consists of core 12a and  
coating or shell 12b, the core consists essentially of a  
dielectric material such as silica, and the shell consists  
essentially of silver halide. Further, with this particle,  
shell 12b is disposed immediately over and substantially  
completely covers core 12a. This particle does not itself  
include any metal and thus does not exhibit the plasmon  
resonance effect. However, the silver halide in the particle  
may be changed to metal silver, either to form a layer of  
30       metal silver on the particle or to help form a layer of

1 another metal thereon, and to thereby form a particle that  
does exhibit the plasmon resonance effect.

5 In particle 14 of Figure 2, a metal coating such as  
silver, copper, aluminum, gold or palladium is disposed  
between the dielectric core and the silver halide coating to  
increase the sensitivity of the silver halide to light. This  
increased sensitivity is caused by the plasmon resonance  
effect produced by the metal coating. More specifically,  
10 particle 14 consists of dielectric core 14a, metal coating  
14b disposed immediately over and covering that core, and a  
layer of silver halide 14c disposed immediately over and  
covering layer 14b.

15 Particle 16 of Figure 3 is similar to particle 14  
of Figure 2 in that both of these particles include a  
dielectric core, one coating of silver halide and a second  
coating of a metal. The order of these coatings in particle  
16, though, is the reverse of the order of these coatings in  
particle 14. More specifically, particle 16 consists of  
20 dielectric core 16a, a layer of silver halide 16b disposed  
immediately over and covering core 16a, and a layer of a  
metal 16c disposed immediately over and covering the silver  
halide coating 16b.

25 Particle 20 of Figure 4 comprises a dielectric core  
20a, a layer of one metal 20b disposed over core 20a and a  
layer of another metal 20c disposed over metal layer 20b.  
Preferably, coating 20b completely covers core 20a, and  
coating 20c completely covers coating 20b. Particle 22 of  
30 Figure 5 is one specie of the general type of particle shown  
in Figure 4. More specifically, particle 22 comprises a  
dielectric core 22a, a layer of silver 22b disposed over core  
22a, and a layer of another metal 22c disposed over the

-8-

1 silver layer 22b with the specific particle configuration  
shown in Figure 5 coating 22b completely covers core 22a, and  
coating 22c completely covers coating 22b.

For certain applications, it may be preferred to  
5 provide the nanoparticles of the present invention with an  
outer coating of a polymer material, for example, to prevent  
the particle from reacting chemically with any medium or  
environment in which the particle is used. This principle is  
generally illustrated in Figures 6 and 7. Figure 6 shows  
10 particle 24 comprising core 24a, first coating 24b and second  
coating 24c. Core 24a consists essentially of a dielectric  
material, coating 24b consists essentially of a metal and is  
disposed immediately over core 24a, and coating 24c consists  
essentially of a polymer material and is disposed immediately  
15 over shell 24b. Coating 24b may completely cover core 24a,  
and coating 24c may completely cover coating 24b. Figure 7  
shows particle 26 comprising core 26a, first coating 26b and  
second coating 26c. Core 26a consists essentially of a  
dielectric material, coating 26b consists essentially of  
20 silver halide and is disposed immediately over core 26a, and  
shell 26c consists essentially of a polymer material and is  
disposed immediately over and completely covers shell 26b.  
Coating 26b may completely cover core 26a, and coating 26c  
may completely cover coating 26a.

25 It may also be desirable to provide nanoparticles  
of this invention with interior coatings or shells of a  
polymer material, either to prevent other coatings or shells  
of the particles from chemically reacting with each other, or  
to prevent the core of the particle from chemically reacting  
30 with a coating or shell of the particle. This principle is

-9-

1 generally illustrated in Figures 8 and 9, which disclose  
particles 30 and 32 respectively.

Particle 30 is similar to particle 16 in that both  
of these particles include an inside dielectric core, a first  
metal coating and a second, silver halide coating.

5 Particles 30 and 16 differ in that the former particle  
includes a third, polymeric coating disposed between the  
metal coating and the silver halide coating. More  
specifically, particle 26 includes core 30a and coatings 30b,  
10 c and d. Core 30a consists essentially of a dielectric  
material, and coating 30b consists essentially of a metal and  
is disposed immediately over and core 30a. Coating 30c  
consists of a polymeric material and is disposed immediately  
over shell 30b, and shell 30d consists essentially of silver  
15 halide and is disposed immediately over shell 30c. With the  
specific arrangement illustrated in Figure 8, coating 30b  
substantially completely covers core 30a, coating 30c  
substantially completely covers coating 30b, and coating 30d  
substantially completely covers coating 30c.

20 Particle 32 is similar to particle 20, and both of  
these particles include a dielectric core and two metal  
coatings or shells. Particle 32 includes a further polymeric  
coating located between the two metal coatings to chemically  
insulate these two metal coatings from each other. To  
25 elaborate, particle 32 comprises core 32a and coatings 32b, c  
and d. Core 32a consists essentially of a dielectric  
material, and coating 32b consists essentially of a metal and  
is disposed immediately over core 32a. Coating 32c consists  
essentially of a polymeric material and is disposed  
30 immediately over coating 32b; and coating 32d consists  
essentially of a metal, which may or may not be the same as

-10-

- 1 the metal of coating 32b, and is disposed immediately over polymeric coating 32c. Each of coatings 32b, c and d may form a respective one, at least substantially complete shell. With such an arrangement, coating 32b substantially
- 5 completely covers core 32a, coating 32c substantially completely covers coating 32b, and coating 32d substantially completely covers coating 32c.

Figures 1-9 are only representative of nanoparticles formed according to the present invention, and in particular, only illustrate the general relationship between the cores and the coatings or shells of the particles. In any nanoparticle of this invention, the particle and the core thereof may have any suitable shapes, and specifically, the particles and the cores may have shapes other than spherical.

10 For instance, the particles and the cores may be cylindrical or ellipsoidal, have a thread-like shape, or be crystalline shaped. The actual crystal form of the core may be any suitable form; and, for example, these cores may be:  
Tetragonal crystal forms,  
15 Orthorhombic crystal forms,  
Monoclinic crystal forms,  
Triclinic crystal forms,  
Isometric crystal forms,  
Hexagonal crystal forms.

20 Also the shapes of the nanoparticles may change as they are made.

25 Further, any suitable dielectric material may be used in these particles; and, in particular, the dielectric material may be linear or non-linear.

30 As used herein, the term "dielectric" material refers to a material which is a non-conductor or a

-11-

1 semi-conductor. The conductivity of this material may range  
from as low as 0, but preferably  $10^{-40}$ , to as high as  $10^6$   
mhos. In a preferred embodiment, the conductivity ranges  
from  $10^{-40}$  to  $10^5$  mhos. In a most preferred embodiment the  
conductivity ranges from  $10^{-30}$  to  $10^4$  mhos. Examples of  
5 dielectric core include glass, silica, cadmium sulfide,  
gallium arsenide, polydiacetylene, lead sulfide, titanium  
dioxide, polymethylacrylate (PMMA), silver bromide, carbon  
fibers, copper sulfide, silver sulfide and the like.

10 In addition, as the term is used herein, "metal"  
includes any material having a negative dielectric constant,  
and so can include super conductors, conducting polymers,  
materials with an anomolous dispersion of carrier electrons,  
and heavily doped semi conductors where free carrier electron  
motion dominates the dielectric function.

15 The types of metals that can be coated onto the  
dielectric core in accordance with the methodology of the  
present invention include the transition metals, the  
lanthanides and the Group IIIA metals. The especially  
preferred transition metals include the Group VIII and IB  
20 metals, and Group IIIA metals, especially copper, silver,  
gold, iron, nickel, palladium, platinum, cobalt, rhodium,  
iridium, ruthenium, aluminum and the like. Especially  
preferred metals include copper, silver, gold, nickel,  
palladium, platinum and aluminum.

25 In accordance with the present invention, the  
metal-halide coated nonoparticles can be prepared by  
providing a source of metal ions and a source of halide ions  
in a liquid carrier having dispersed therein charged  
30 colloidal dielectric particles and reacting the halide ions  
with the metal ions in the presence of the dielectric

-12-

1 particles to form coatings of metal halide over individual  
dielectric particles.

For example, using this procedure, silver halide  
coated dielectric particles, such as particle 12 of Figure 1  
5 can be prepared. More specifically, this procedure,  
generally, comprises the steps of providing a source of  
silver ions and a source of halide ions in a liquid carrier  
having dispersed therein charged colloidal dielectric  
particles, and reacting the halide ions with the silver ions  
10 in the presence of the dielectric particles to form coatings  
of silver halide over individual dielectric particles.

Figure 10 outlines one preferred method for  
carrying out this process but this procedure is exemplary and  
is equally applicable to the other metal halides coating  
15 dielectric particles. This method generally comprises the  
steps of providing an aqueous solution including negatively  
charged colloidal dielectric nanoparticles, positively  
charged silver ions, and a halide, and reacting the halide  
with the silver ions to bond, or grow, coatings of silver  
20 halide on, and preferably completely covering, individual  
dielectric particles. Preferably, the concentrations of  
dielectric particles, silver ions and halide in the solution,  
and the length of time over which the coatings are allowed to  
grow on the dielectric particles, are selected so that  
25 coatings of a uniform preselected thickness are grown on  
those particles. The specific order in which the dielectric  
particles, the silver ions and the halide are added to the  
aqueous solution is not critical; and, for example, the  
dielectric particles may be dispersed in the solution, then  
30 the silver ions may be added, and then the halide may be  
added.

-13-

1       With a preferred process, after the dielectric  
1       particles are added to the solution, the pH of that solution  
is adjusted to and thereafter maintained at a level slightly  
above 2, and even more preferably, between about 3 and 5.  
5       With this procedure, the dielectric particles do not have to  
be negatively charged when they are added to the solution,  
and, instead, the acidity of the aqueous solution causes the  
dielectric particles to become negatively charged once the  
10      particles are in the solution. Further, with the preferred  
process, the initial concentration of the silver ions in the  
solution is relatively low, less than  $10^{-4}$  M; the initial  
concentration of the halide in the solution is slightly  
greater than, such as about 10% greater than, the  
concentration of the silver ions in the solution; and also,  
15      the solution is constantly stirred while the halide is being  
added to it.

20      The silver ions may be added to the solution in any  
suitable form, and for instance, these ions may be added in  
the form of a silver salt that is soluble in aqueous  
solution, e.g., silver nitrate. Likewise, the halide that is  
added to the solution may be any suitable halide, such as an  
alkali halide, e.g., sodium bromide, potassium bromide,  
potassium chloride, sodium chloride and the like. In  
addition, any suitable dielectric may be used in the  
25      above-discussed process, and the dielectric may be linear or  
non-linear and may have any suitable shape and size. For  
example, the dielectric particles may be spherically shaped  
silica particles. When, first, the dielectric particles are  
these silica particles, second, the silver ions are added to  
the solution in the form of silver nitrate, and third, the  
30      halide is sodium bromide, then the silver from the silver

-14-

1 nitrate reacts with the bromide from the sodium bromide to  
form silver bromide, which bonds to and forms layers over the  
silica particles.

5 A metal coating on a dielectric particle, such as  
coating 14b of particle 14, or coating 24b of particle 24,  
may be made by a process, generally, comprising the steps of  
providing a source of metal ions, a source of a secondary  
alcohol, preferably a lower secondary alkanol containing 3-7  
10 carbon atoms and a source of a ketone preferable containing  
3-7 carbon atoms in an anaerobic liquid carrier having  
dispersed therein charged dielectric particles, and exposing  
the liquid carrier to light, preferably ultraviolet light to  
cause the metal ions to attach to the dielectric particles  
and form metal coatings over individual dielectric particles.

15 As used herein, the term lower alkyl, when used  
alone or in combination, contains 1-7 carbon atoms. These  
alkyl groups may be straight chained or branched and include  
such groups as methyl, ethyl, propyl, isopropyl, butyl,  
sec-butyl, isobutyl, t-butyl, pentyl, amyl, hexyl and the  
20 like.

As used herein, a secondary alkanol refers to a  
lower alkyl alcohol in which the hydroxy group is attached to  
a secondary carbon. Such groups include isopropanol,  
sec-butanol, and the like.

25 The preferred ketone is acetone.

Figure 11 outlines one preferred method for  
carrying out this process. This method generally comprises  
the steps of providing an aqueous solution including  
negatively charged colloidal dielectric particles, metal  
30 ions, isopropanol and acetone; removing oxygen from the  
solution; and exposing the solution to ultraviolet light to  
cause the metal ions to attach to the

-15-

1 dielectric particles and form metal coatings completely  
covering individual dielectric particles. Preferably, the  
concentrations of the dielectric particles, the metal ions,  
the isopropanol and the acetone, and the length of time the  
5 solution is exposed to the ultraviolet light are selected so  
that coatings of a uniform preselected thickness are formed  
on the dielectric particles.

In the above-discussed procedure, without wishing  
to be bound, it is believed that the acetone absorbs energy  
10 from the ultraviolet light and then reacts with isopropanol  
to form isopropyl radicals. These radicals are powerful  
reducing agents and cause metal ions that have become  
attached to the dielectric particles to form metal molecules.  
The particular order in which the dielectric particles, the  
15 metal ions, the isopropanol and the acetone are added to the  
aqueous solution is not critical; and, for instance, the  
isopropanol and acetone may be added to the solution, the  
dielectric particles may then be dispersed in the solution,  
and then the metals may be added.

20 In the above procedure, it is preferred that the  
light source used contain ultraviolet light. It is preferred  
that the light source contain wavelengths from 150-550 nm.  
The preferred wavelengths range from 200-400 nm.

25 Furthermore, it is preferred that the intensity of  
light used range from 50 watts to 1.5 kilowatts, with the  
preferred intensity ranging from 250-1000 watts. Especially  
preferred intensity range from 350-550 watts, with an  
intensity of about 450 watts being the most preferred.

30 In a preferred method, as with the method outlined  
in Figure 10, after the dielectric particles are added to the  
solution, the pH of the solution is adjusted to and

-16-

1 thereafter maintained at a level slightly above 2, and even  
more preferably, between about 3 and 5. In this way, the  
dielectric particles do not have to be negatively charged  
when they are added to the solution and the acidity of the  
5 aqueous solution causes the dielectric particles to become  
negatively charged. In addition, the initial concentration  
of the metal ions in the solution is relatively low, such as  
 $2 \times 10^{-4}$  M; and the initial concentrations of the ketone,  
e.g., acetone, and secondary alcohol, e.g., isopropanol in  
10 the solution are about equal to each other and much greater  
than, such as about 400 times greater than, the initial  
concentration of the metal ions in the solution. In  
addition, preferably the solution is stirred while exposed to  
the ultraviolet light.

15 Numerous specific types of metal coatings may be  
made using a procedure as described above, and for example,  
the process may be used to form silver coated dielectric  
particles, gold coated particles or palladium coated  
particles. In addition, the metal ions may be provided in  
20 the solution in any suitable manner; and, for example, these  
ions may be provided by adding a water soluble metal salt  
such as silver nitrate, to the solution.

25 Moreover, any suitable dielectric may be used in  
the above-discussed process, and the dielectric may be linear  
of non-linear and may have any suitable shape and size. For  
instance, the dielectric particles may be spherically shaped  
silica particles. When such dielectric particles are used,  
and the metal ions are added to the solution in the form of  
silver nitrate, then the ultraviolet light, in combination  
30 with the acetone and the isopropanol, causes the silver ions

-17-

1 to bond to and form metal silver coatings over the silica particles.

The following example illustrates this process for forming a metal silver coating over the silica particles.

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-18-

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EXAMPLE 1

An aqueous solution is prepared by mixing the following solutions in a 50 ml beaker:

5 (1) 0.5 ml of 0.01 M  $\text{AgNO}_3$   
(2) 0.5 ml of 0.50 M  $\text{SiO}_2$  of low porosity particles. The particle diameter was chosen to be between 5 to 20 nanometers, although other sizes can be readily substituted,  
(3) 1.5 ml of pure isopropanol,  
10 (4) 1.5 ml of pure acetone.  
10 All chemicals used are of reagent grade quality, unless otherwise specified. The above mixture are diluted with 16 ml of distilled water, and the pH adjusted to be between 4 to 5 by dropwise addition of a 0.01 M nitric acid solution. In this pH range, the silica particles are negatively charged,  
15 causing the positively charged silver ions to be bound to the surface. After thorough mixing by stirring for one minute using a magnetic stirrer, the sample is transferred to a UV photolysis vessel, equipped with a quartz window and  
20 provision for careful deoxygenation by bubbling nitrogen gas for one hour. It is important that no oxygen be present in the solution. The sample is irradiated by a 450 Watt Hg-Xe lamp for one hour, with gentle stirring continued by means of a magnetic stirrer. The solution color, and consequently the thickness of the coat, can be controlled by adjusting the  
25 period of illumination by UV light. This forms the basis for the preparation of the silver coated silica particles in the present example.

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-19-

1 Metal, e.g., silver coated dielectric particles may  
also be made by a process employing photoreduction of metal  
(e.g., silver) halide, and one such exemplary process is  
outlined in Figure 12. In this process, silver halide coated  
5 dielectric particles are made, for example, by the process  
discussed above in connection with Figure 10, and then the  
coated particles are exposed to light to change the silver  
halide coatings over the individual particles to metal silver  
coatings.

10 Preferably, though, a more integrated process is  
used to form metal coated dielectric particles. This  
process, generally, comprises the steps of providing a source  
of metal ions, a source of halide ions and a source of an  
electron hole scavenger in a liquid carrier having dispersed  
15 therein negatively charged colloidal dielectric particles,  
reacting the metal ions with the halide ions in the presence  
of the dielectric particles and the electron hole scavenger  
to form metal halide coatings over individual dielectric  
particles, and exposing the liquid carrier to light to change  
the silver halide coatings to metallic silver coatings.

20 Figure 13 outlines a preferred method to implement this  
process using silver ions. In accordance with this method,  
dielectric particles are dispersed in a solution including  
silver ions, a halide and an electron hole scavenger, and the  
silver ions react with the halide to form silver halide  
25 coatings over, and which may completely cover, individual  
dielectric particles. The solution is then exposed to  
ultraviolet light, and this light changes the silver halide  
coatings to silver coatings. Preferably, the concentrations  
of the dielectric particles, the silver ions, the halide and  
30 the electron hole scavenger in the solution, and the length

-20-

1 of time the solution is exposed to the ultraviolet light are selected so that coatings of a uniform preselected thickness are formed on the dielectric particles.

5 Preferably, with this process, the initial concentration of metal (e.g., silver) ions in the solution is greater than the initial concentration of the halide in the solution; and for instance, the former concentration may be about 5 time the latter concentration. The metal ions may be in the solution in any suitable form, and for instance, if 10 silver is the metal ion, these ions may be added to the solution in the form of a metal salt that is soluble in aqueous solutions, e.g., silver nitrate. Similarly, the halide that is added to the solution may be any suitable halide, such as alkali halide, e.g., sodium bromide, 15 potassium bromide, sodium chloride, potassium chloride and the like. Further, any suitable dielectric may be used in this process, and the dielectric may be linear or non-linear and have any suitable shape and size. For example, the dielectric particles may be spherically shaped silica 20 particles. When (i) the dielectric particles are the silica particles, (ii) the silver ions are added to the solution in the form of silver nitrate, and (iii) the halide is sodium bromide, then the silver from the silver nitrate reacts with the bromide from the sodium bromide to form silver bromide 25 coatings on the dielectric particles; and the ultraviolet light, in the presence of EDTA, then reduces the silver bromide coatings to metallic silver.

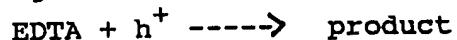
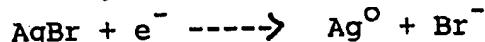
-21-

EXAMPLE 2

1 The following example illustrates this process for  
forming silver coated dielectric particles. Metallic silver  
on  $\text{SiO}_2$  particles can be obtained by photoreduction of silver  
halides, which are typically prepared in the presence of  
5 excess  $\text{Ag}^+$  ions. A hole ( $\text{h}^+$ ) scavenger, EDTA, is added to  
the solution. One ml of a 0.002 M NaBr solution is added to  
19 ml of a solution which is prepared in a 50 ml beaker by  
mixing the following:

10 (1) 1 ml of 0.01 M  $\text{AgNO}_3$ ,  
(2) 0.5 ml of 0.50 M of low porosity  $\text{SiO}_2$  particles. The  
particle diameter was 12 nanometers, although other sizes can  
be readily substituted,  
(3) 1 ml of 0.02 M EDTA,  
15 (4) 16 ml of distilled water.

15 After thorough mixing, the solution is transferred to a 1 cm  
UV quartz cuvette and exposed to a 375 Watt tungsten halogen  
light source. Under these conditions, very little light is  
actually absorbed since the colloidal  $\text{AgBr}$  has a very low  
absorbance above 350 nm. A possible mechanism for the  
20 reduction process is given by: -



25 The duration of illumination, which is in the order of  
minutes, determines the color of the silver coated silica  
particles. This color is a result of the thickness of the  
silver layer, and can range from yellow to a purplish gray.

-22-

1 Once the silver coated silica spheres are prepared,  
they are purified by dialysis and then placed in a sodium  
dodecyl sulfate micellar solution, or a micro emulsion.

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-23-

1 A variation of the process described above may be  
employed to form metal coatings other than silver on  
nanoparticles, and this variation utilizes the fact that  
metallic silver on the dielectric particles will act as a  
catalyst to help grow metal coatings on those particles from  
5 other metal ions in the solution. In accordance with this  
variation, which is outlined in Figure 14, a liquid carrier,  
or a solution, is provided including dielectric particles  
having silver halide formed on those particles, at least a  
10 portion of the silver halide on individual nanoparticles is  
changed to metallic silver, and ions of a metal are added to  
the solution to form coatings of that metal completely  
covering individual dielectric particles, with the metallic  
silver on those particles acting as a catalyst to accelerate  
15 the formation of the metal coatings. These metal ions may be  
added to the solution in any suitable manner, and for  
instance, conventional photographic developing solutions may  
be added to the solution to reduce the metal ions.

Only minute amounts of metallic silver are needed  
20 on the dielectric particles to help grow the metal coatings  
thereon; and hence, in the above-described process, it is  
only necessary to form minute amounts of silver halide on the  
dielectric particles. Alternatively, complete coatings of  
silver halide may be formed on the dielectric particles, with  
25 only minute amounts of the silver halide on individual  
particles being changed to metallic silver on individual  
particles, and then these minute amounts of metallic silver  
may be used to help form metal coatings completely covering  
the silver halide that remain on the dielectric particles.  
30 The resulting product comprises a dielectric core, a first  
coating of silver halide that substantially completely covers

-24-

1 the electric core, and a second coating of a metal that  
completely covers the layer of silver halide.

5 The following example illustrates the coating of  
silver on an dielectric core of silver bromide. The silver  
bromide nanoparticles exposed briefly to intense UV light in  
the presence of EDTA have optical extinction spectra similar  
to those computed for distribution of silver coated silver  
bromide nanoparticles. By intense, it is meant that the  
intensity of the light ranges from 50 watts to 1.5 kilowatts,  
10 with the preferred range being 250-550 watts, and the most  
preferred having a range of 350-550 watts.

15 As clearly shown by the following discussion, with  
shorter exposure time, the plasmon resonance maximum is  
shifted to lower wavelengths, a result consistent with theory  
so long as the coat thickness increases with exposure to  
light. The resonance maximum of the distributions of coated  
particles can be controllably shifted to 600 to 700 nm.

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-25-

EXAMPLE 3

1 Silver bromide colloids were prepared by rapidly  
mixing equal volumes of  $\text{AgNO}_3$  and  $\text{NaBr}$  solutions. A growth  
stabilizer (SDS) and an electron donor (EDTA) were added  
5 immediately after precipitation. Typically the final  
concentrations were  $1 \times 10^{-4}$  M  $\text{Br}^-$ ,  $4 \times 10^{-4}$  M  $\text{Ag}^+$ ,  $5 \times 10^{-4}$   
M SDS, and  $5 \times 10^{-4}$  M EDTA. The concentration of SDS was far  
below the critical micellization concentration ( $10^{-2}$  M).  
Freshly prepared solutions were exposed to light from a 450  
10 Watt Hg-Xe lamp for a few seconds. With the shortest  
exposures the spectra appeared blue. With longer exposures  
the solutions appeared orange. When ammonia, which dissolves  
AgBr by forming complexes with  $\text{Ag}^+$ , was added to any of the  
illuminated solutions the color changed to a yellow color  
15 characteristic of small metallic silver colloids.

15 The particle size distributions were characterized  
with transmission electron microscopy (JEOL 1200EX). A  
typical micrograph is shown in Fig 19. A size distribution  
consistent with the limited micrograph data is the log normal  
distribution.

20 
$$N(r) = N_0 \exp(-((\ln(r) - \ln(r_m))/\ln(s))^2),$$
  
with  $r_m$  equal to 1 nm or less and  $s$  in the range of 4 to 4.5  
nm. The size distributions as determined by TEM did not  
appear to change markedly with exposure to light.

25 After the addition of ammonia to any of the  
illuminated samples only small particles having diameters 5  
nm or less were observed in the TEM (Fig 20). The most  
likely interpretation is that only part of the AgBr was  
reduced to Ag during the illumination and that the larger  
30 particles are AgBr/Ag composites.

-26-

1 Example optical extinction spectra measured shortly  
after exposure are shown in Figs. 21a) to d). The exposure  
time and/or EDTA concentration, and hence the reduction of  
Ag<sup>+</sup>, increases in going from a) to d). The peak extinction  
5 shifts to shorter wavelengths as the illumination time is  
increased. This result is consistent with theory so long as  
the coat thickness increases with exposure. A spectrum of  
the ammonia treated solution, shown in Fig 21e), is typical  
10 of homogeneous silver nanoparticles. The general shapes of  
the above spectra are readily reproducible. At comparable  
illumination times, in the absence of Br<sup>-</sup>, the appearance of  
color in a given sample is negligible.

15 Theoretical optical extinction spectra of  
individual silver coated spheres are shown in Fig. 22. The  
peak of the theoretical extinction shifts from red to blue as  
the ratio of coat thickness to core radius increases. This  
data is consistent with the measured spectra where the  
absorption maxima shifts toward the blue as the time of  
exposure increases, since the coat thickness should increase  
20 with exposure time. The computed spectra are very sensitive  
to the coat thickness. The measured spectra are much more  
broad than the spectra shown in Fig. 22 because of the  
distributions of core diameters and coat thicknesses.

25 The magnitudes of the extinction spectra are also  
characteristic of silver coated particles. For example, at a  
wavelength of 700 nm the extinction cross section per unit  
volume of silver is 100's of times larger in a silver coated  
nanoparticle having the appropriate ratio of core radius to  
coat thickness than it is in a solid silver sphere. The fact  
30 that the theoretical extinction is so large can be used to  
help verify that the particles are coated with silver.

-27-

1 However, since there is a broad distribution of sizes care  
must be taken in making the comparison.

5 Here we started with the size distribution of core  
particles described by the above equation, then used trial  
and error to determine the distributions of coat thicknesses  
required to match the measured spectra, and then found that  
the magnitudes of the spectra were within the range of values  
expected from the initial concentrations of  $\text{Ag}^+$  and  $\text{Br}^-$ .

10 The assumptions made in computing the spectra are  
as follows:

1. The reduced silver is in the form of a smooth  
coat on the surface of a spherical  $\text{AgBr}$   
particle. The extinction efficiencies were  
computed using the separation of variables  
solution for concentric spheres based on  
algorithms.
2. The size distribution of the core particles is  
described by the log-normal distribution of the  
above equation. The values of  $N_0$  were  
determined by setting the total volume of all  
the particles prior to illumination in the  
distribution equal to the volume of  $\text{AgBr}$ . The  
initial total volume of  $\text{AgBr}$  was determined by  
solving the ionic equilibria equations  
including the  $\text{Ag}^+$ -EDTA complex.
3. The size distribution of the coat thickness is  
a Gaussian, typically with a standard deviation  
of 2 to 8 nm.
4. The silver coat may be formed either from the  
reduction of the silver halide of the initial  
particle, or from the reduction of  $\text{Ag}^+$  from

-28-

1 solution. Computations have been done for each  
of the two limiting cases.

5 5. The total extinction is computed by numerically  
integrating over distributions of core radii  
and coat thicknesses.

5  $b_e(\lambda) = \int N_n(r_c) N_g(t) \Omega(r_c, t, m_c, m_t, \lambda) \pi r^2 dr_c dt$   
where  $N_n$  is the size distribution of the cores,  
10  $N_g$  is the size distribution of the coats,  $\Omega$  is  
the extinction efficiency,  $m_c$  is the refractive  
index of the core, and  $m_t$  is the refractive  
index of the coat. Typically the integrations  
over cores were from  $r=2$  to  $r=18$ .

15 6. The refractive index of the silver was computer  
from the data of Hagemann et al. in J. Op. Soc.  
Am., 65, 742-744 (1975) and Kerker, in J. Op.  
Soc. Am. B., 1327-1329 (1985) either by itself,  
20 or combined with a Drude model in which the  
increased electron scattering at the surfaces  
of the very thin coat was taken into account.  
The refractive index data of Johnson and  
Christy in Phy. Rev. B, 6, 4370-4379 (1972) was  
also used for some computations not shown.  
Linear interpolation was used to obtain the  
values of refractive index at points not in the  
data.

25 7. The refractive index of AgBr was obtained by  
combining the data from White, J. Opt. Soc. Am.,  
62, 212 (1972) and James, "Theory of the  
Photographic Process," McMillan (1977) p 216.

30 Fig. 23 shows a measured spectrum and two computed  
spectra. In the topmost curve the Ag in the coat is assumed

-29-

1 to come only from the solution, i.e., the AgBr cores are not  
reduced in size as the coat grows. In the bottom curve the  
Ag in the coat is assumed to come only from the reduction of  
AgBr at the surface of the particle and so the core shrinks  
5 as the coat grows. Since the measured curve lies between the  
two computed spectra, the magnitudes of the plasmon enhanced  
extinction is in the range of values computed.

10 The main parameters that can be adjusted in fitting  
the distributions to the spectra are: 1) the thickness and  
standard deviation of the coats and the limits of the  
numerical integration for the coats. 2) the size  
15 distribution and the limits of integration for the cores. 3)  
the date for the refractive index of silver. 4) the  
fraction of the reduced silver that came from solution. The  
computed spectra are very sensitive to the distributions of  
cores and coats chosen and to the limits of integration,  
which also define the size distributions. The computed  
spectra depend on the refractive index of silver used.  
20 However, by varying the size distributions, similar spectra  
can be obtained with the different models for silver. The  
effect of the different assumptions about the source of the  
Ag for the coat can be seen in Fig. 23. In a preliminary  
experiment without excess silver a spectrum similar to that  
shown in Fig. 21d) was generated.

25 Without wishing to be bound, it is believed that  
the silver coat is formed by the coalescing of many small  
silver particles. The coat may also contain some AgBr or  
voids, but it is homogeneous enough to have a refractive  
index similar to that of bulk islver. The bonds between the  
30 particles may be relatively weak because the coat breaks into

-30-

1 many small particles when the solution is treated with  
1 ammonia.

5 It might have been thought that the spectra could be accounted for by nonspherical silver particles. The fact that ammonia, which dissolves AgBr but not Ag, reduces the spectrum to that of small solid silver particles, and the fact that the particles in the TEM do not have large eccentricities, argue against this hypotheses. Also, the particle shapes do not seem to be related to the colors of  
10 the solutions.

10 In summary, the predicted tunability of the surface-plasmon resonance frequency and enhanced extinction at longer wavelengths was experimentaly confirmed with Ag-AgBr colloidal composites. The particles scatter as if the Ag is smoothly coated on the AgBr.

15 Silver coated dielectric particles may also be formed by a process utilizing chemical reduction of silver ions by hydroquinone at elevated temperatures. The following example, generally outlined in Figure 15, illustrates this  
20 process.

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-31-

EXAMPLE 4

1 100 ml of a silica solution (particle diameter 7  
nm) which had been purified by overnight dialysis was  
transferred to a 250 ml beaker, and the pH adjusted to 4.0 by  
5 dropwise addition of 0.01 M nitric acid. This was heated to  
90°C, and 0.01 M  $\text{AgNO}_3$  solution added dropwise under gentle  
stirring to achieve the final concentration shown in the  
table below. After about 2 minutes, sufficient quantity of  
10 0.01 M hydroquinone was added in a similar manner. The  
reduction to metallic silver takes place gradually over a  
time period of about five minutes, accompanied by a color  
change from pale yellow to dark brown. The rate of silver  
deposition by this method can be controlled by varying the  
temperature between 85 and 95°C. A transparent solution is  
15 obtained in every case, and is allowed to cool and then  
purified by dialysis.

The following table summarizes the experimental  
conditions, including final concentrations, which were used  
in four different sets:

	I	II	III	IV
20	$\text{SiO}_2$ 1%	1%	1%	1%
	$\text{AgNO}_3$ $5.0 \times 10^{-4}$	$1.0 \times 10^{-3}$	$1.5 \times 10^{-3}$	$2.0 \times 10^{-3}$
	Hydro- quinone $5.0 \times 10^{-5}$	$1.0 \times 10^{-4}$	$1.5 \times 10^{-4}$	$2.0 \times 10^{-4}$

20 The amount of silver deposited increases from I to  
IV, and is evident from the color of the solution (light  
yellow to dark brown). Electron microscopy also provided  
evidential support. The optical absorption spectra show the  
presence of a single peak maximum at about 400 nm.

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-32-

1 ELECTRON MICROSCOPIC RESULTS:

1 Solution 1 consists of particles which are smaller and better defined, appear darker, and were in the size range of 10 to 30 nm. In solution II, III and IV, the particle 5 size range was found to be between 40 to 100 nm, the particles were similarly dark, but contained elongated as well as spherical shapes. The final size distribution may be due in part to the non uniform size of the silica core particles, found to be between 7 to 11 nm by electron 10 microscopy.

With all of the processes described above, after the coated particles are prepared, they may be removed from the solution in which they were prepared by dialysis, and then placed in a sodium dodecyl sulfate micellar solution or 15 a micro emulsion. Additional coatings of either silver halide, a metal or a polymer, may then be added until the desired final configuration is reached. Polymer coating of any of these particles may be readily achieved in a solution by the well known emulsion polymerization method, in which a 20 suitable amount of monomer and initiator have been added.

For instance, the following process, outlined in Figure 16, shows how a polymer coating may be made on a silver coated particle.

The following aqueous stock solutions were 25 prepared:

- (I) 0.1 M  $\text{KH}_2\text{PO}_4$ ,
- (II) 0.1 M NaOH,
- (III) 2% solution of sodium salt of styrene sulfonic acid, NaSS (comonomer),
- 30 (IC) 3% solution of  $\text{K}_2\text{S}_2\text{O}_8$ .

-33-

1 All solutions were prepared in doubly distilled  
water, and all chemicals were reagent grade.

5 131.6 ml of a 1% solution of the silver coated  
silica particles were transferred to a three necked flask. 8  
ml of solution IV, followed by 6.4 ml of solution II, were  
added with constant stirring using a magnetic stirrer. The  
flask was equipped with a condenser, and a platinum  
thermometer, which, in combination with a thermoregulator and  
a heating mantle, allowed regulation of the temperature of  
10 the flask to 65 ± 1°C. At this temperature, nitrogen gas was  
bubbled through the mixture continuously, and 30 ml of  
styrene added. After 15 minutes, 10 ml of solution III were  
added, and after another 20 minutes 4 ml of the initiator,  
solution IV, were added. Depending upon the thickness of the  
15 polymer film desired, the reaction can be terminated by  
addition of 25 ml of a 1% solution of hydroquinone, and  
cooling the reaction mixture to room temperature. The  
particles are filtered, washed several times with doubly  
distilled water, resuspended in water, and further purified  
20 by dialysis.

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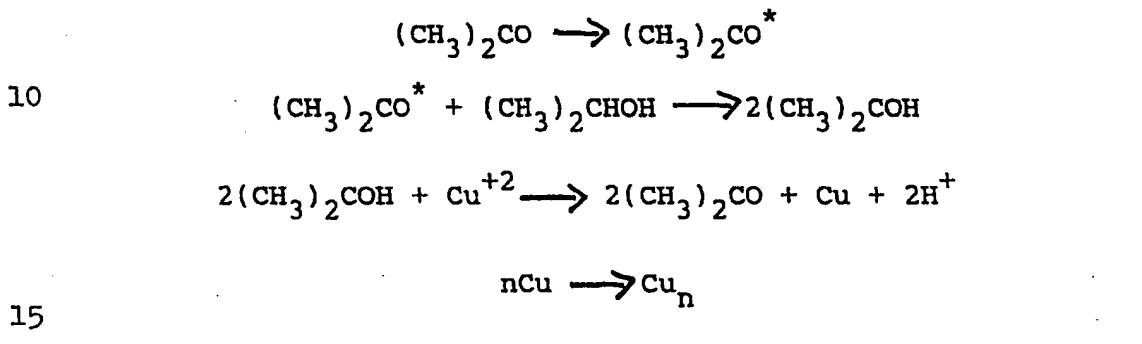
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EXAMPLE 5

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Coating of carbon fibres with copper was carried out by photochemical reduction of  $\text{Cu}^{++}$  using highly reductive short lived 1-hydroxy-1-methylethyl radicals. These radicals were produced in situ by illuminating a mixture of 1 M acetone and 1 M propanol-2 with a UV source of Hg-Xe lamp operated at 450 watt. The reaction can be presented by



15 Two different solutions of  $\text{Cu}^{++}$  ( $1 \times 10^{-2}$  M and  $1 \times 10^{-3}$  M) were used to achieve two different coating thicknesses. Both solutions contained 1 M acetone, 1 M propanol-2, and carbon fibers. The illumination time was two hours.

20 These coated fibres, washed with distilled water and observed under an optical microscope, show a very fine and smooth coating and visibly exhibit a metallic lustre of copper. The amount of copper on these fibres was detected 25 using atomic absorption spectroscopy after removing the coat with 1 M nitric acid. The presence of copper on these fibres was also confirmed using Energy Dispersive Spectroscopy (EDS), which shows a peak for copper. The thickness of the coat can be controlled by the copper concentration in 30 solution and the duration of illumination. It can be readily varied in the range of tens of nanometers to microns.

1 The processes discussed above may be used in  
various combinations to form particles of a desired  
configuration. For example, Figure 17 generally outlines a  
5 procedure to make particle 20 of Figure 4. First, metal  
coating 20b is formed over dielectric core 20a, for example  
using the method illustrated in Figure 13; and then silver  
halide coating 20c is made over metal layer 20b, for instance  
by generally following the method shown in Figure 10.  
10 Similarly, Figure 18 generally illustrates a procedure to  
make particle 22 of Figure 5. In this procedure, first,  
metal coating 22b is formed over dielectric core 22a, for  
example by the process described above in connection with  
Figure 11, then polymer coating 22c is applied over coating  
22b, and then silver halide layer 22d is formed over coating  
22c, for example by generally following the procedure  
15 discussed above in connection with Figure 10.

Methodology of the present invention are not  
20 limited to coating metals on a nanoparticle. Methods  
described herein can also be used to plate metals onto a  
substrate. This is especially useful if the substrate is a  
catalyst support system. By using methodology described  
herein, the catalyst support system can be coated with  
metals, e.g., Group VIII metals and provide a surface on  
which catalysis can occur. Catalyst support systems include  
25 zeolites, polystyrene, metal oxide, (e.g., titanium oxide)  
polymer support and the like.

30 The methods of the present invention can be used to  
coat other surfaces. For example, methodology of the present  
invention can be used to coat dielectric material, such as  
silica, glass, cadmium sulfide, gallium arsenide,  
polydiacetylene, lead sulfide, PMMA, silver bromide, carbon  
fibers, copper sulfide, silver sulfide, glass fibers, and the  
like.

1 The methods of the present invention can also be  
used to plate metals onto other metals, especially Group VIII  
metals.

5 The metals that can be plated onto the substrate  
include the lanthanide, the Group VIII metals, the Group IA  
metals and the Group IIIA metals. The preferred metals are  
silver, copper, gold, iron, nickel, palladium, platinum,  
cobalt, rhodium, iridium, ruthenium and aluminum.

10 One of the preferred methods for coating metals  
onto the surface of a substrate entails providing a source of  
metal ions, secondary lower alkanol and a lower alkyl ketone  
distributed in an anaerobic liquid carrier containing said  
substrate and exposing the liquid carrier to light to cause  
the metal ions to form metal and to plate onto the surface of  
15 the substrate. This procedure is used in the same manner as  
that described herein for coating a dielectric particle with  
the secondary alcohol, alkyl ketone, source of metal ions and  
light.

20 The other procedure for coating metals (e.g.  
silver) onto surfaces is the photoreduction method described  
herein. A substrate is coated with metal (e.g. silver)  
halide by reacting a source of metal (e.g. silver) ions with  
a source of halide ions on the surface of a substrate in an  
anaerobic carrier containing an electron scavenger and  
optionally a growth stabilizer. The substrate surface is  
25 then illuminated with light, whereby the metal (e.g. silver)  
halide coatings is converted to metal (e.g. silver) coating.  
This procedure is thus used in the same manner as described  
herein for coating dielectric particles.

-37-

1        Although the text hereinabove refers to halides,  
1        the halides may be replaced with organic anions, thereby  
      forming other metal complexes. A property of these organic  
      anions is that they must be capable of forming stable  
5        complexes. These organic ions include such anions as  
5        acetate, formate, citrate, EDTA, malonate, and polypeptides  
      prepared from the natural amino acids, such as poly GLU, poly  
      ASP, and the like.

10      While it is apparent that the invention herein  
      disclosed is well calculated to fulfill the objects  
10      previously stated, it will be appreciated that numerous  
      modifications and embodiments may be devised by those skilled  
      in the art, and it is intended that the appended claims cover  
      all such modifications and embodiments as fall within the  
15      true spirit and scope of the present invention.

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WHAT IS CLAIMED IS:

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1. A method of forming silver halide coated dielectric particles, comprising the steps of:

5 providing a source of ions and a source of halide ions in a liquid carrier having dispersed therein charged colloidal dielectric particles; and

10

reacting the halide ions with the silver ions in the presence of the dielectric particles to form coatings of silver halide over individual dielectric particles.

15

2. A method according to claim 1, wherein the reacting step includes the step of reacting the halide ions with the silver ions to form silver halide coatings of a selected, uniform thickness on individual dielectrical particles.

20

3. A method according to claim 2, wherein the reacting step includes the step of reacting the halide ions with the silver ions for a preselected length of time to form the silver halide coatings on the dielectric particles.

25

4. A method according to claim 1, wherein the reacting step includes the step of forming coatings of silver halide completely covering individual dielectric particles.

25

5. A method according to claim 2, wherein the providing step includes the steps of:

providing the liquid carrier with a source of a given initial concentration of silver ions; and

providing the liquid carrier with a source of an initial concentration of halide slightly greater than said given concentration.

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-39-

6. A method according to claim 5, wherein said  
1 initial concentration of halide ions is about 10% greater  
than said given concentration.

7. A method according to claim 6, wherein said  
5 given concentration is  $10^{-2}$  molar.

8. A method according to claim 2, wherein the  
providing step includes the steps of:

introducing the dielectric particles and the silver  
ions into the liquid carrier, and then introducing the halide  
ions into the solution; and

10 stirring the liquid carrier while the halide ions  
are being introduced into the liquid carrier.

9. A method according to claim 2, wherein the  
providing step includes the steps of:

15 introducing silver nitrate into the solution;  
introducing sodium bromide into the solution; and  
dispersing silica nanoparticles in the solution.

10. A method of coating a metal onto the surface  
of a substrate which comprises providing a source of metal  
ions, a secondary lower alkanol and a lower alkyl ketone,  
20 each of which is uniformly distributed in an anaerobic liquid  
carrier containing said substrate and

25 exposing the liquid carrier to light having  
sufficient intensity and wavelength to cause the metal ions  
to form metal and to plate onto the surface of said  
substrate.

30 11. The method of Claim 10 wherein the exposing  
step includes the step of exposing the liquid carrier to  
light to form metal coatings of a selected uniform thickness  
on the surface of the substrate.

-40-

1 12. The method according to Claim 10 wherein the exposing step includes the step of forming metal coatings completely covering the substrate.

5 13. The method according to Claim 10 wherein the initial concentration of each of the secondary alkanol and alkyl ketone is greater than the initial concentration of the source of the metal ions.

10 14. The method according to Claim 13 wherein the initial concentration of each of the alkanol and alkyl ketone is about 400 times greater than the concentration of the source of metal ions.

15 15. The method according to Claim 10 wherein the exposing step includes the step of stirring the liquid carrier while exposing the liquid carrier to light.

16. The method according to Claim 10 wherein the providing step includes the step of introducing a water soluble metal salt into the liquid carrier.

20 17. The method according to Claim 10 wherein the wavelength of light used ranges from 150-550 nm.

18. The method according to Claim 17 wherein the wavelength of light used ranges from 200-400 nm.

25 19. The method according to Claim 10 wherein the intensity of light ranges from 50 watts to 1.5 kilowatts.

20. The method according to Claim 19 wherein the intensity of light ranges from 350-550 watts.

21. The method according to Claim 20 wherein the intensity of light is about 450 watts.

22. The method according to Claim 10 wherein the metal is a Group IIIA metal, Group IB metal, Group VIII metal or a lanthanide.

-41-

1           23. The method according to Claim 22 wherein the metal is a Group IB or Group VIII metal.

5           24. The method according to Claim 23 wherein the metal is silver, copper, gold, iron, nickel, palladium, platinum, cobalt, rhodium, iridium, ruthenium or aluminum.

10          25. The method according to Claim 24 wherein the metal is silver, copper, gold, nickel, palladium, or platinum.

15          26. The method according to Claim 10 wherein the secondary alcohol is isopropanol.

20          27. The method according to Claim 10 wherein the alkyl ketone is acetone.

25          28. The method according to Claim 10 wherein the substrate is a dielectric material.

30          29. The method according to Claim 28 wherein the dielectric material has a conductivity ranging from  $10^{-40}$  to  $10^{+6}$  mhos.

35          30. The method according to Claim 28 wherein the dielectric material is a catalyst support.

40          31. The method according to Claim 28 wherein the dielectric material is zeolite, polystyrene, metal oxide, glass, silca, cadmium sulfide, gallium arsenide, polydiacetylene, lead sulfide, PMMA, silver bromide, carbon fibers, copper sulfide, silver sulfide or glass fibers.

45          32. The method according to Claim 31 wherein the metal oxide is titanium oxide.

50          33. The method according to Claim 10 wherein the substrate is a metal.

55          34. The method according to Claim 10 wherein the substrate is a Group VIII metal.

-42-

1 35. A method of forming metal coated dielectric nanoparticles, comprising the steps of:

5 providing a source of metal ions, a source of an alcohol and a source of ketone in an anaerobic liquid carrier having dispersed therein charged dielectric particles; and

10 exposing the liquid carrier to light to cause the metal ions to form metal coatings over individual dielectric particles.

15 36. A method according to claim 35, wherein the exposing step includes the step of exposing the liquid carrier to light to form metal coatings of a selected, uniform thickness on individual dielectric particles.

20 37. A method according to claim 35, wherein the exposing step includes the step of forming metal coatings completely covering individual dielectric particles.

25 38. A method according to claim 35, wherein the providing step includes the steps of:

30 providing the liquid carrier with a source of an initial, given concentration of metal ions; and

35 providing the liquid carrier with a source of initial concentrations of alcohol and ketone greater than said given concentration.

40 39. A method according to claim 38, wherein said initial concentrations of each of the alcohol and ketone is about 400 times said given concentration.

45 40. A method according to claim 35, wherein the exposing step includes the step of stirring the liquid carrier while exposing the liquid carrier to light.

50 41. A method according to claim 35, wherein the providing step includes the step of introducing a water soluble metal salt into the solution.

-43-

1 42. A method according to claim 41, wherein:  
the water soluble salt is silver nitrate; and  
the providing step further includes the step of  
dispersing silica nanoparticles into the solution.

5 43. A method of forming silver coated dielectric  
nanoparticles, comprising the steps of:  
forming silver halide coated nanoparticles; and  
exposing the coated nanoparticles to light to  
change the silver halide to metallic silver to form metal  
coatings over individual nanoparticles.

10 44. A method according to claim 43, wherein the  
step of forming the silver halide coated nanoparticles  
includes the steps of:

15 providing a source of silver ions and a source of  
halide ions in a liquid carrier having dispersed therein  
charged colloidal dielectric particles; and  
reacting the halide ions with the silver ions in  
the presence of the dielectric particles to form coatings of  
silver halide covering individual dielectric particles.

20 45. A method according to claim 44, wherein the  
reacting step includes the step of reacting the halogen of  
the halide ions with the silver ions to form silver halide  
coatings of a selected, uniform thickness on individual  
dielectric particles.

25 46. A method according to claim 43, wherein the  
exposing step includes the step of changing substantially all  
of the silver halide on each of a multitude of nanoparticles  
to metallic silver.

30 47. A method according to claim 46, wherein the  
providing step includes the steps of:

-44-

1 providing the liquid carrier with a source of an initial, given concentration of silver ions; and

5 providing the liquid carrier with a source of an initial concentration of halide ions slightly greater than said given concentration.

10 48. A method according to claim 47, wherein the providing step includes the steps of:

introducing silver nitrate into the liquid carrier; introducing sodium bromide into the liquid carrier;

and

15 10 introducing silica nanoparticles into the liquid carrier.

15 49. A method of coating a silver onto the surface of a substrate which comprises providing an anerobic liquid carrier containing therein a metal halide coated onto a substrate and an electron hole scavenger which is uniformly distributed in the liquid carrier;

20 exposing the liquid carrier to light of sufficient wavelength and intensity to convert the silver halide coatings to metal coatings.

25 50. The method according to Claim 49 wherein a growth stabilizer is additionally present.

51. The method according to Claim 50 wherein the silver halide is formed from reacting a source of silver ions with a source of halide ions on the surface of said substrate in the anerobic liquid carrier.

52. The method of Claim 50 wherein the light used is ultraviolet light.

30 53. The method according to Claim 50 wherein the exposing step includes the step of exposing the liquid

-45-

1 carrier to ultraviolet light to form metallic coatings of a selected uniform thickness on said substrate.

5 54. The method according to Claim 50 wherein the initial concentration of the source of silver ions is greater than the initial concentration of the source of halide ions.

5 55. The method according to Claim 54 wherein said initial concentration of the source of silver ions is about 5 times the initial concentration of halide ions.

10 56. The method according to Claim 50 wherein the electron hole scavenger is EDTA.

57. The method according to Claim 50 wherein the growth stabilizes the SDS.

58. The method according to Claim 50 wherein the wavelength of light used ranges from 200-400 nm.

15 59. The method according to Claim 50 wherein the intensity of light ranges from 50 watts to 1.5 kilowatts.

60. The method according to Claim 59 wherein the intensity of light ranges from 350-550 watts.

20 61. The method according to Claim 50 wherein the substrate is a dielectric material.

62. The method according to Claim 50 wherein the dielectric material has a conductivity ranging from  $10^{-40}$  to  $10^{+6}$  mhos.

25 63. The method according to Claim 62 wherein the dielectric material is a catalyst support.

64. The method according to Claim 61 wherein the dielectric material is zeolite, polystyrene, metal oxide, glass, silica, cadmium, sulfide, gallium arsenide, polydiacetylene, lead sulfide, PMMA, silver bromide, carbon fibers, copper sulfide, or silver sulfide.

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-46-

1 65. The method according to Claim 64 wherein the metal oxide is titanium oxide.

66. The method according to Claim 50 wherein the substrate is a metal.

5 67. The method according to Claim 66 wherein the substrate is a Group VIII metal.

68. The method according to Claim 50 wherein the source of metal ions is silver nitrate, the source of halide ions is sodium bromide and the substrate is silica.

10 69. A method of forming silver coated dielectric particles, comprising the steps of:

providing a source of silver metal ions, a source of halide ions and a source of an electron hole scavenger in a liquid carrier having dispersed therein negatively charged colloidal dielectric particles;

15 70 reacting the silver ions with the halide ions in the presence of the dielectric particles and the electron hole scavenger to form silver halide coatings completely covering individual dielectric particles; and

20 71 exposing the liquid carrier to light to change the silver halide coatings to metallic silver coatings.

70. A method according to claim 69, wherein the exposing step includes the step of exposing the liquid carrier to ultraviolet light to form silver metallic coatings of a selected, uniform thickness on individual dielectric particles.

71. A method according to claim 70, wherein the providing step includes the steps of:

providing the liquid carrier with a source of an initial, given concentration of the halide ions; and

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-47-

1 providing the liquid carrier with a source of an  
initial concentration of silver ions greater than said given  
concentration.

72. A method according to claim 71, wherein said  
initial concentration of silver ions is about 5 times said  
5 given concentration.

73. A method according to claim 72, wherein said  
given concentration is about  $1 \times 10^{-4}$  molar.

74. A method according to claim 69, wherein:  
10 the reacting step includes the step of reacting the  
silver ions with the halide ions to form metal halide  
coatings of a preselected, uniform thickness on individual  
dielectric particles; and

15 the exposing step includes the step of exposing the  
liquid carrier to light to change substantially all of the  
metal halide on individual particles to metallic silver to  
form metallic silver coatings of said preselected, uniform  
thickness on the particles.

75. The process according to Claim 69 wherein the  
light is ultraviolet light.

20 76. The process according to Claim 69 wherein the  
electron hole scavanger is EDTA.

77. The process according to Claim 69 wherein a  
growth stabilizer is additinally present.

25 78. The process according to Claim 77 wherein the  
growth stabilizer is SDS.

79. The process according to Claim 69 wherein the  
source of metal ions is silver nitrate, the source of halide  
ion is sodium bromide ant the dielectric particles is silica  
manoparticles.

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-48-

1 80. A method of forming metal coated dielectric  
particles, comprising the steps of:

5 providing a liquid carrier having dispersed therein  
dielectric particles having silver halide on the surfaces  
thereof;

10 changing at least a portion of the silver halide on  
individual particles to metallic silver;  
15 introducing metal ions into the liquid carrier; and  
forming metal coatings on the particles from the  
metal ions, and including the step of using the metallic  
silver on the particles as a catalyst to accelerate the  
formation of the metal coatings.

20 81. A method according to claim 80, wherein:  
the providing step includes the step of providing  
the liquid carrier with dielectric particles completely  
25 covered with silver halide coatings;

the changing step includes the step of changing  
only a minute portion of the silver halide on individual  
particles to metallic silver, wherein silver halide coatings  
remain substantially completely covering individual  
20 particles; and

the forming step includes the step of forming the  
metal coatings over the silver halide coatings.

25 82. A method according to claim 80, wherein:  
the providing step includes the step of providing  
the liquid carrier with dielectric particles completely  
covered with silver halide coatings;  
the changing step includes the step of changing  
substantially all of the silver halide on individual  
30 particles to metallic silver to form metallic silver coatings  
completely covering individual particles; and

-49-

1 the forming step includes the step of forming the  
metal coatings over the metallic silver coatings.

83. A method of forming silver coated dielectric  
particles, comprising the steps of:

5 providing a source of silver ions in a liquid  
carrier having dispersed therein charged colloidal dielectric  
particles;

heating the liquid carrier;

providing a liquid carrier having particles  
10 dispersed therein; and

introducing  $K_2S_2O_8$  and NaOH into the liquid  
carrier.

84. A method according to claim 83, wherein the  
heating step includes the step of heating the liquid carrier  
15 to about 90°C.

85. A method according to claim 83, wherein:

the providing step includes the step of providing  
the liquid carrier with a given initial concentration of  
silver ions; and

20 the introducing step includes the step of  
introducing into the initial concentration of the reducing  
agent about one-tenth said given concentration.

86. A method of forming polymer coatings over a  
particle comprising the steps of:

25 providing a liquid carrier having particles  
dispersed therein;

introducing a monomer into the liquid carrier;

introducing a sodium salt of the monomer into the  
liquid carrier;

30 introducing a polymerization initiator into the  
liquid carrier, wherein the monomer forms a polymer coating  
over the particles.

-50-

1 87. A method according to claim 86, further  
including the step of maintaining the temperature of the  
liquid carrier between about 64 and 66°C.

5 88. A method according to claim 87, further  
including the step of terminating the reaction by introducing  
a reducing agent into the liquid carrier.

89. A method according to claim 88, wherein the  
particles include dielectric cores.

10 90. A method according to claim 89, wherein the  
particles further include metal coatings disposed over the  
dielectric cores.

91. A method according to claim 89, wherein the  
particles further include silver halide coatings disposed  
over the dielectric cores.

15 92. A nanoparticles comprising:  
a dielectric core; and  
a silver halide coating over the dielectric core.  
93. A nanoparticle according to claim 92, further  
comprising a polymer coating over the silver halide coating.  
20 94. A nanoparticle according to claim 92, further  
comprising a metal layer disposed between the dielectric core  
and the silver halide coating.

25 95. A nanoparticle according to claim 94, further  
comprising a layer of a polymeric material disposed between  
the metal layer and the silver halide coating.

96. A nanoparticle according to claim 95, wherein  
the dielectric core is a spherically shaped silica particle.

97. A nanoparticle consisting of:  
a core consisting essentially of a dielectric  
30 material;

-51-

1 a first coating consisting essentially of a metal,  
and disposed immediately over the core of the particle;

2 a second coating consisting essentially of a  
polymeric material, and disposed immediately over the first  
5 coating of the particle; and

5 a third coating consisting essentially of a silver  
halide, and disposed immediately over the second coating of  
the particle.

98. A nanoparticle according to claim 97, wherein  
10 the first coating consists essentially of metallic silver.

99. A nanoparticle comprising:

a dielectric core;  
a metal coating disposed over the dielectric core;  
and

15 a layer of a polymeric material disposed over the  
metal coating.

100. A nanoparticle according to claim 99, further  
comprising another metal coating disposed over the layer of  
polymeric material.

101. A nanoparticle according to claim 99,  
20 wherein:

the dielectric core comprises a spherically shaped  
silica particle; and

the metal coating comprises metallic silver.

102. A nanoparticle consisting of:

25 a dielectric nano-core;  
a metal coating disposed over the dielectric core;  
and

30 a layer of a polymeric material disposed over the  
metal coating.

-52-

1 103. A nanoparticle according to claim 102,  
wherein the metal coating consists essentially of metallic  
silver.

5 104. A nanoparticle comprising:  
a dielectric core;  
a layer of silver disposed over the dielectric  
core; and  
a layer of a metal disposed over the layer of  
silver.

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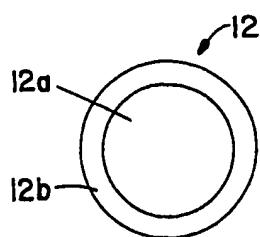


FIG. 1

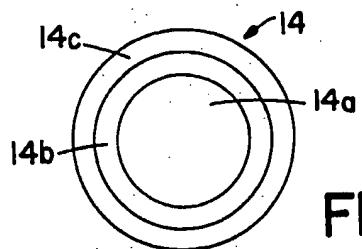


FIG. 2

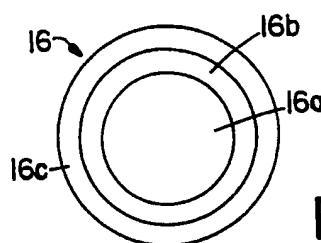


FIG. 3

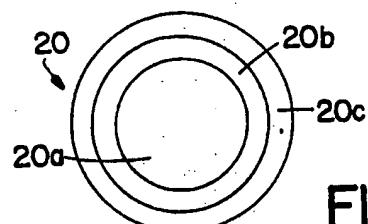


FIG. 4

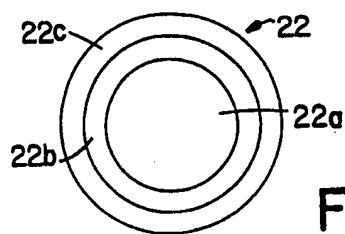


FIG. 5

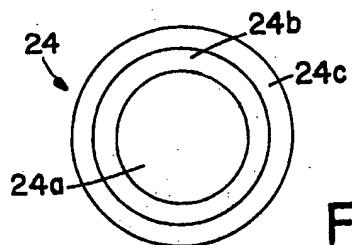


FIG. 6

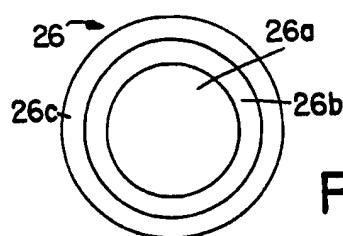


FIG. 7

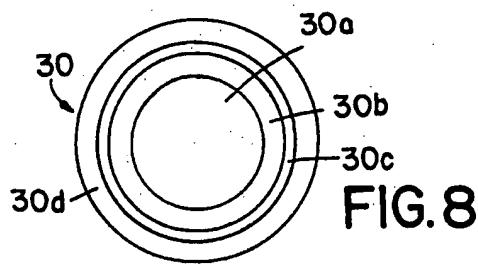


FIG. 8

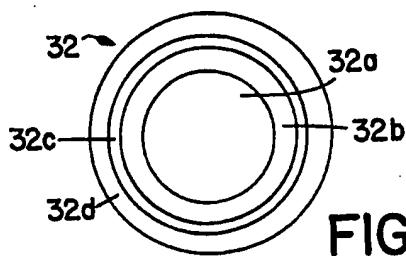


FIG. 9

2 / 10

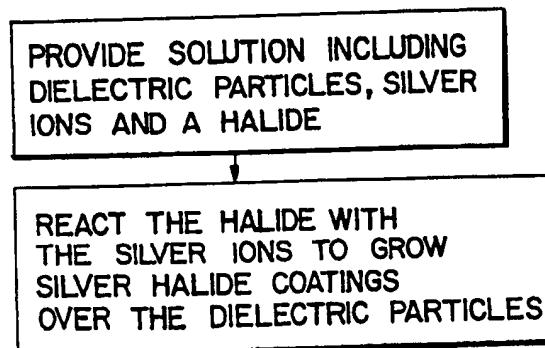


FIG. 10

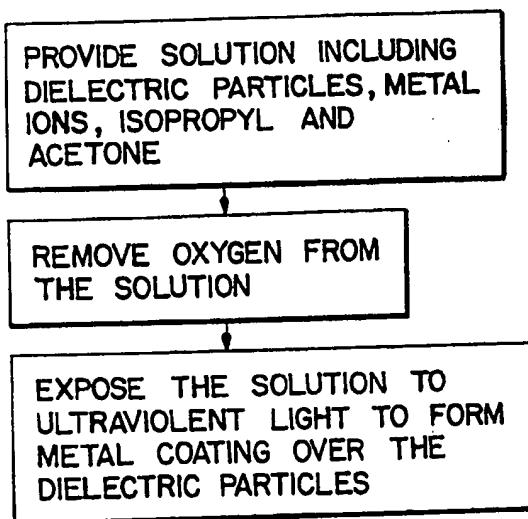


FIG. 11

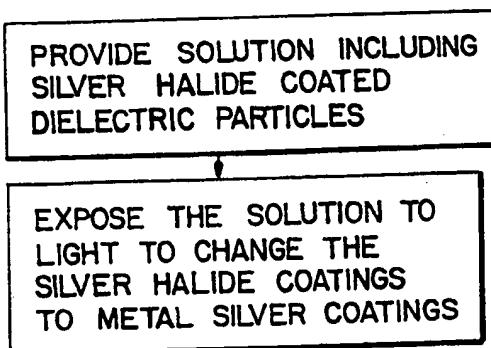


FIG. 12

3 / 10

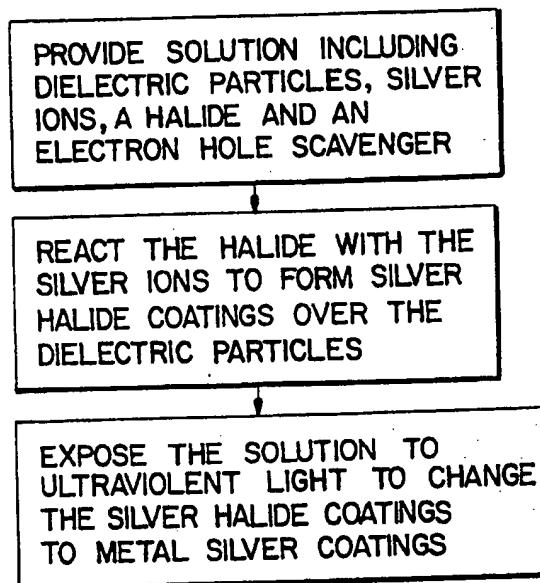


FIG. 13

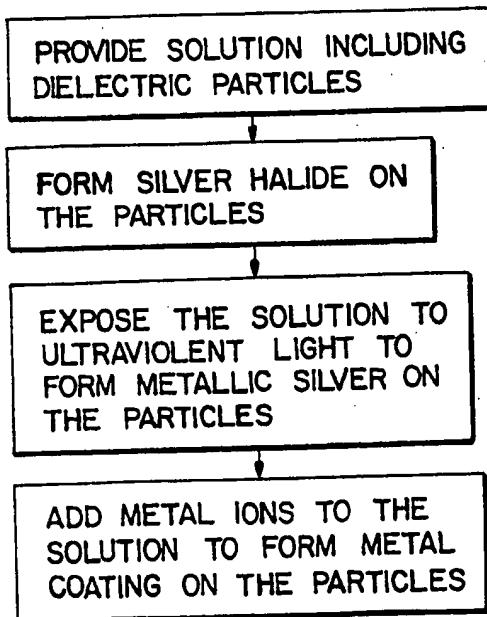


FIG. 14

4 / 10

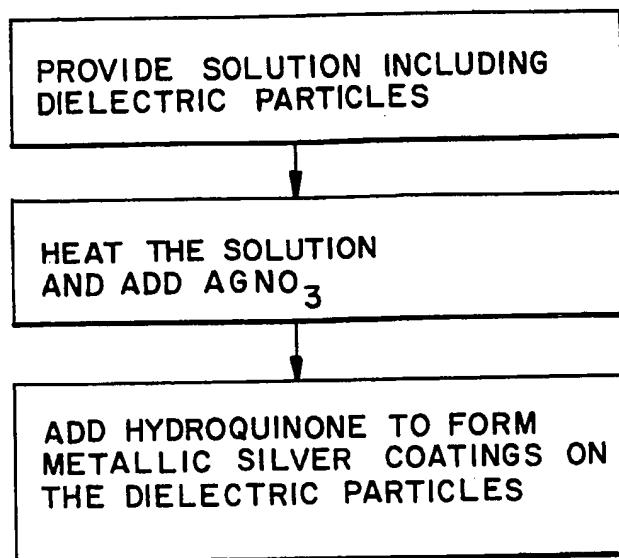


FIG. 15

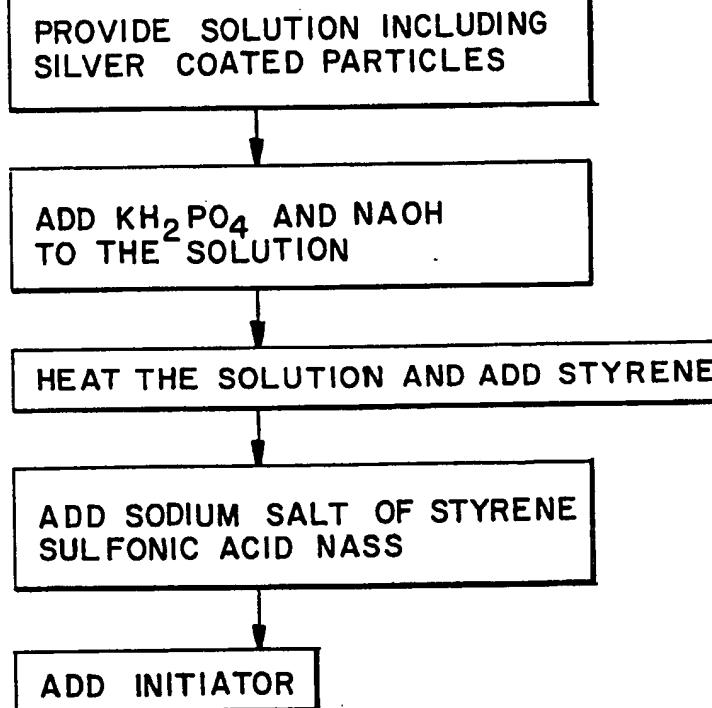


FIG. 16

5 / 10

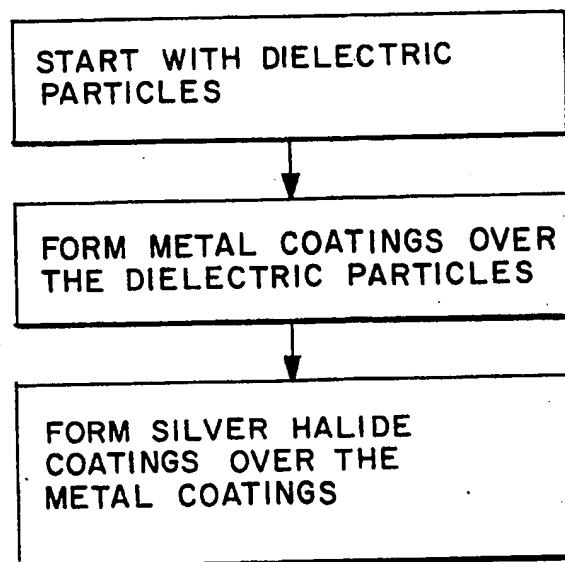


FIG. 17

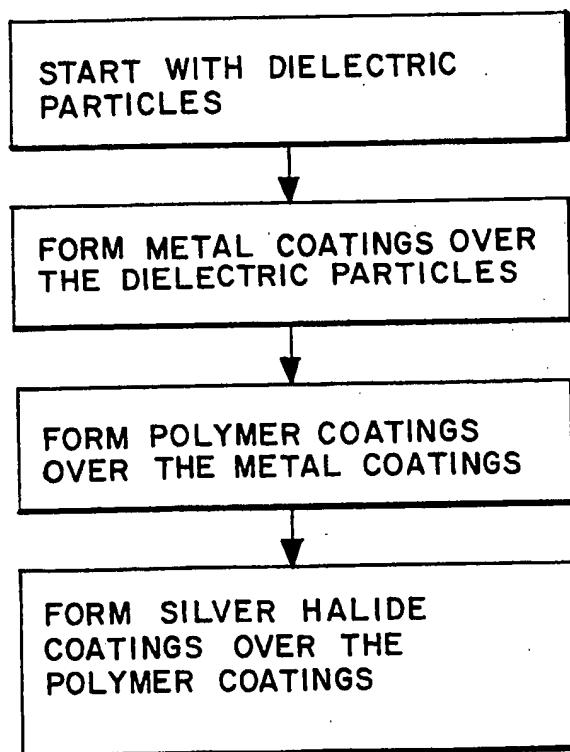


FIG. 18

6/10

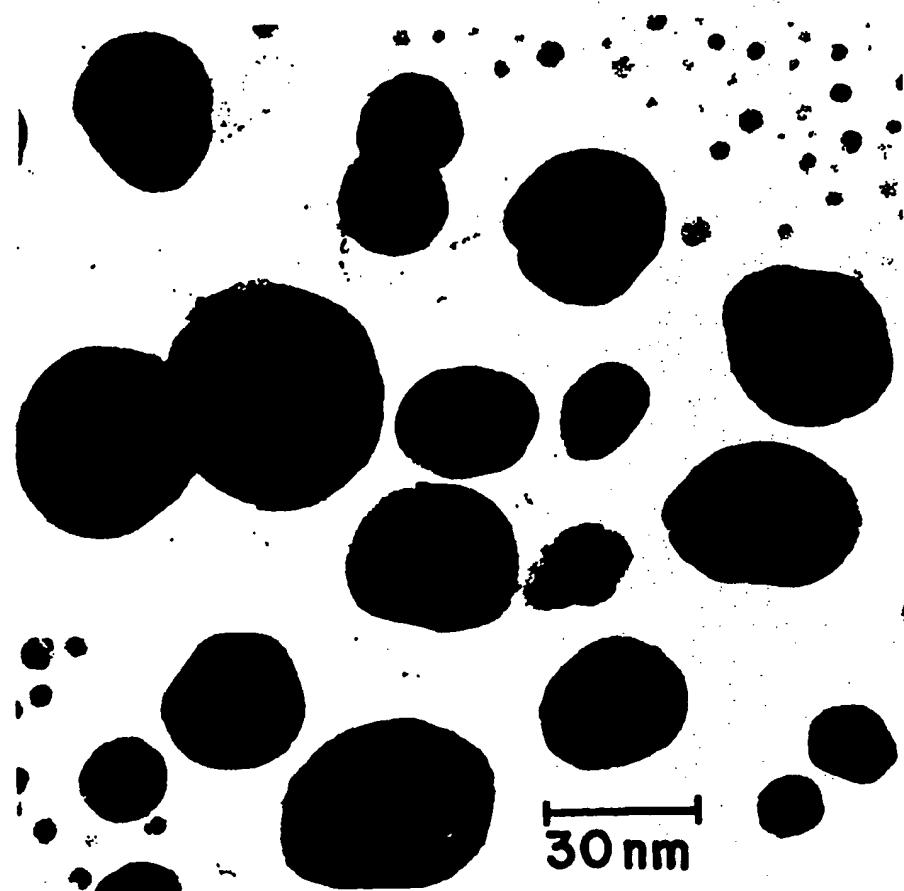


FIG.19

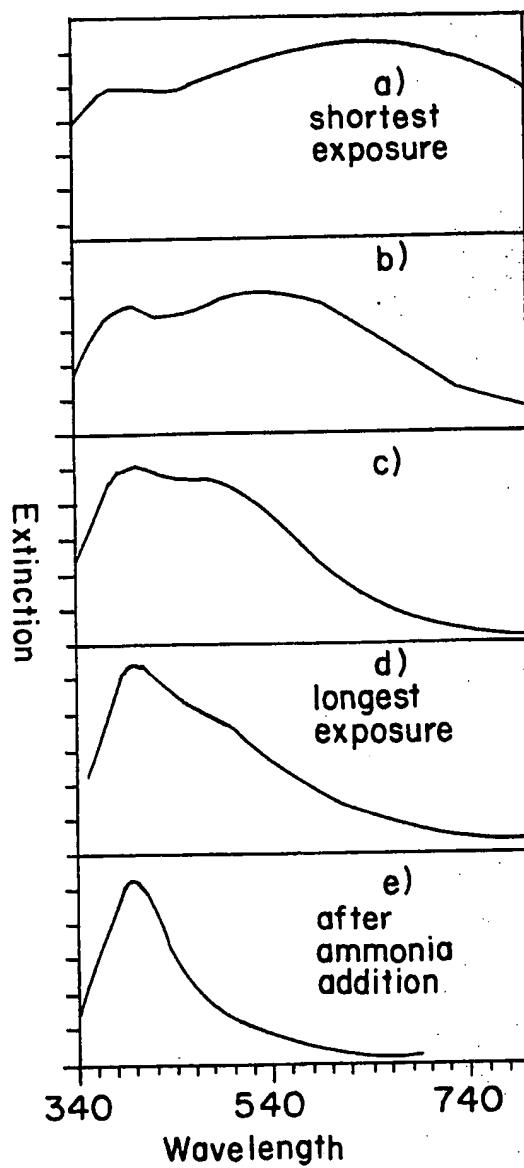
7 / 10



20 nm

FIG. 20

FIG. 21



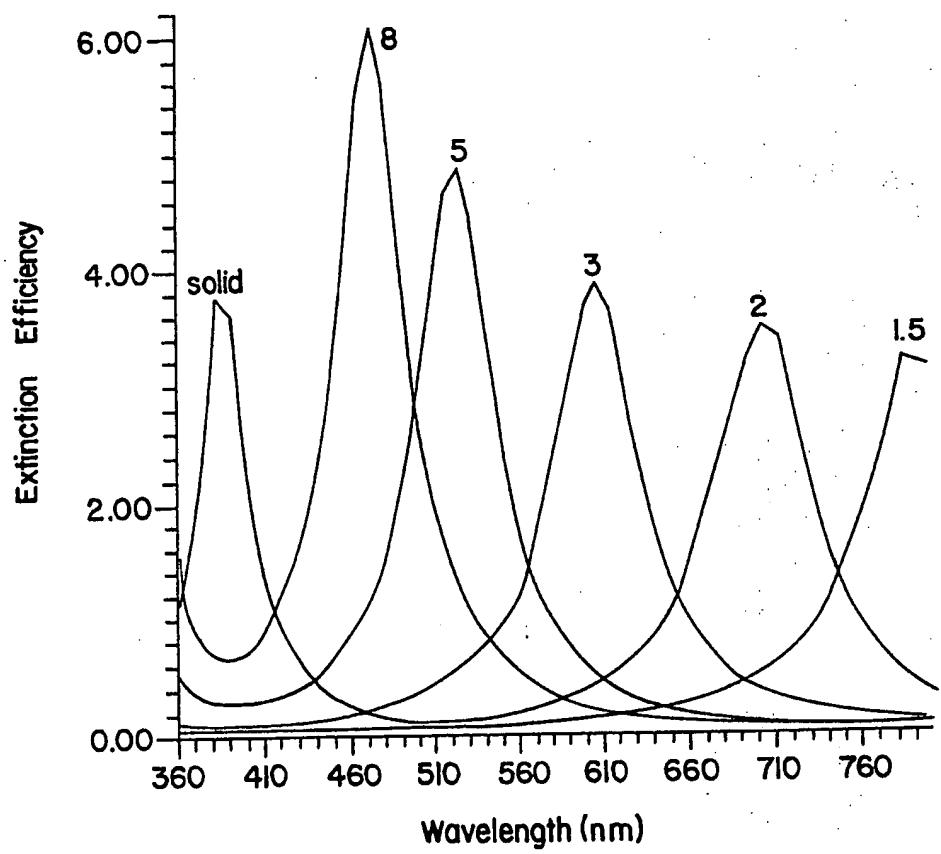


FIG. 22

10 / 10

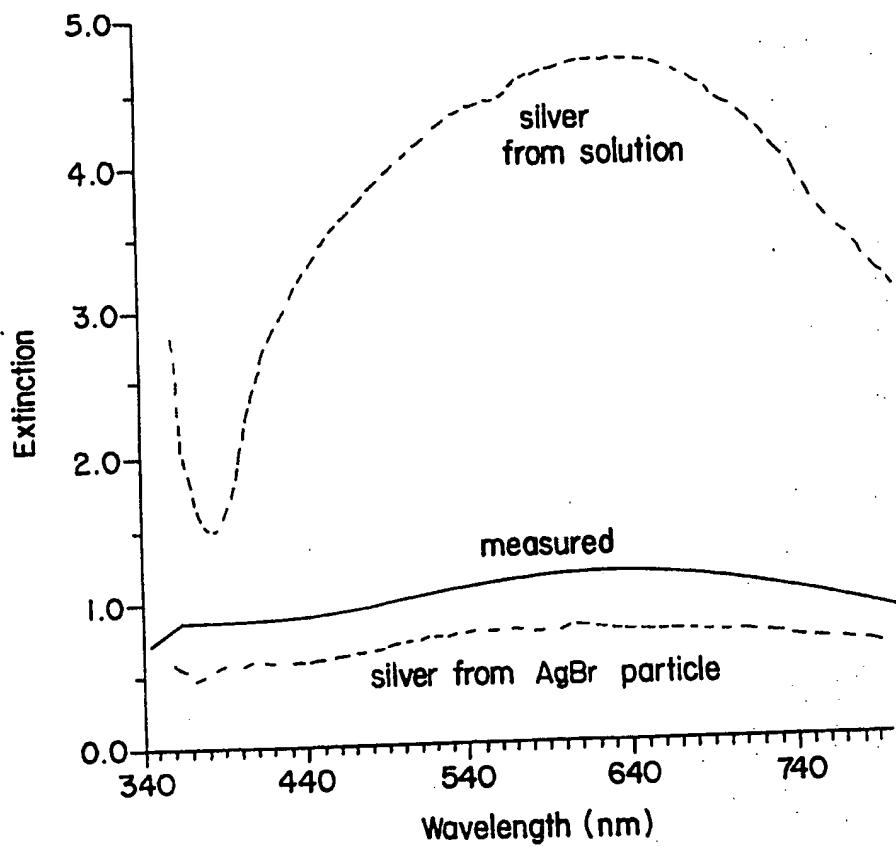


FIG.23